Monitoring Flaring State in the Black Hole X-Ray Binary/ Microquasars GRS 1915+105 and Cyg X-3: Radio Timing with the Korean VLBI Network

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Abstract. Microquasars, nearby stellar-scale analogy of quasars, are producing jets at speeds very close to the speed of light up to 0.98 c. Microquasars are also accreting transient or persistent X-ray binaries. For a decade since its discovery, the phenomena of microquasars have had a great deal of attention. The observation of transient flares and accompanied jet phenomena is one of the highlights in the fields of X-ray, radio and, very recently, infrared astronomy. The recent observations have indicated that the superluminal jets probably are the common nature of the black hole X-ray binaries and, in part, of the neutron star binary sources. The recent development in observational techniques has made it possible to study detailed feature of jet phenomena. In the radio the very long baseline interferometry (VLBI) is required to map images of jets. The first Korean VLBI Network (KVN), recently proposed for the mm-wave multi-channel receiver system of 2.5, 8.5, 23, 43, 86−129 GHz, therefore, can be a promising tool of probing the nature of microquasars. In this paper, we present the strategy of observing microquasar phenomena with radio telescopes in Korea, including KVN, and international collaboration with Japanese VLBI system, VERA. Monitoring program for microquasars with 6−14−21 m array is also presented. As an example radio timing of frequently flaring, radio-bright microquasars such as GRS 1915+105 and Cyg X-3 are discussed.

BLACK HOLE X-RAY BINARIES AS COMPACT RADIO SOURCES

For over 30 years, more than 40 black hole binaries have been detected through X-ray observations (for reviews, [1][2]). There are 18 dynamically confirmed sources with known black hole mass ($\geq 3-4 M_{\odot}$) available. Except three persistent sources, LMC X-1, LMC X-3 and Cyg X-1, almost all are X-ray transients, or X-ray novae (XRNVs), with phenomena of outbursts, or flares. Four dynamically confirmed transients have been observed with multiple, two or more spatially separate, jet components. These are GRO J1655-40 (XRNV Sco 1994), XTE J1550-564, SAX J1819.3-2525 (V4641 Sgr) and GRS 1915+105. The so-called black hole candidates, without known companion's radial velocities and masses, are believed almost certainly to be a black hole since outburst light curves and spectra are similar to those in the dynamically confirmed black holes.

Transients are usually bright enough to be detected at outbursts, but become undetectable as they return to quiescence. The next outburst dates are unpredictable, ranging from a few to a hundred years. Recurrent flares of a year or two have been observed in a few confirmed black hole binaries and black hole candidates. In addition, there are a few neutron star binaries with a few year-long recurrent time scale. Not all of these frequently flaring transients in X-rays, unfortunately, are radio-bright. Neutron star sources are in particular dim in the radio even in their outburst states, except a few sources like LSI +61°303, a Be-binary. The X-ray persistent sources are also dim in the radio (for a review, [3][4][5]).

In the so-called disk instability model, tens to hundreds of years of the recurrent time scale for outbursts, or flares, is generally thought as a reasonable outburst limit cycle (e.g., [6][7]). For most black hole sources, therefore, the fact that only one outburst has been detected seems to be natural. To detect such transient and persistent X-ray binaries in the radio, in particular to map evolving jets, a very small beam size of $\leq$ milliarcsecond (mas) is required in addition to lower flux detectability. The interferometers and the VLBI (Very Long Baseline Interferometry) system are therefore required. In this paper, we present a monitoring program of microquasar phenomena with recently proposed VLBI in Korea.

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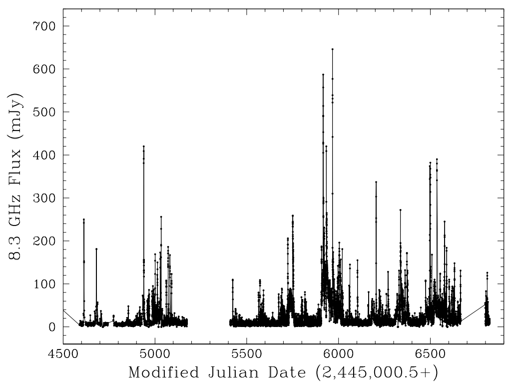

FIGURE 1. Long-term 8.3 GHz radio light curve of GRS 1915+105 observed by the Green Bank Interferometry

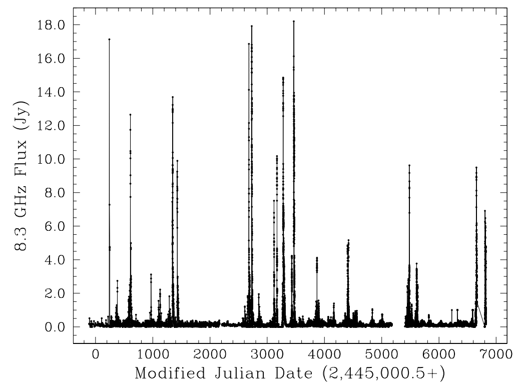

FIGURE 2. Long-term 8.3 GHz radio light curve of Cyg X-3 observed by the Green Bank Interferometry

RADIO TIMING MONITORING OF FREQUENTLY FLARING, RADIO-BRIGHT MICROQUASARS: GRS 1915+105 AND CYG X-3

There are a few peculiar microquasars displaying radio-bright, frequent flares, accompanied with jet features. GRS 1915+105 is perhaps the best target to investigate with VLBI (Figure 1). Another radio-loud, persistent X-ray source with frequent flares is Cyg X-3 (Figures 2 and 3), although we currently do not know the identification of this source, black hole or neutron star.

In figures 1 and 2 we present long-term observations of the radio flux variabilities in GRS 1915+105 and Cyg X-3 observed by the Green Bank Interferometry (GBI; see `http://www.gb.nrao.edu/fgdocs/gbi/arcgbi/` and `http://ftp.gb.nrao.edu/pub/fghigo/gbidata/gdata`).

The chaotic flaring activity could repeat as short as hours, accompanied with unpredictable radio flux rise as high as $\sim$ 700 mJy and $>$ 10 Jy from a few mJy, for GRS 1915 +105 and Cyg X-3, respectively. In 1996, 1998 and 2000, the flaring activities in GRS 1915+105 occurred in about one third, or a quarter of each year. On the contrary, giant flares seem to recur with intervals of a few hundred days to a few years and, in addition, numerous rapid, small time scale minor flares are obvious at $\leq$ a few hundred mJy (Figure 3).

The timing behaviors of these transients are basically irregular in both recurrent time scale and peak fluxes. About 12 different X-ray spectral states are recently proposed for GRS 1915+105 [8]. On the contrary, the radio spectral behavior has not been well understood. The radio-X-ray correlation is one of highlighted issues in the study of X-ray binaries. Recently an universal relationship between the radio and X-ray flux, S_R and S_X, based on observation of a few microquasars, has been suggested: $S_R \propto S_X^{+0.7}$ [9]. Multi-wavelength timing observations, therefore, are important to understand the nature of flaring activities of GRS 1915+105 and Cyg X-3.

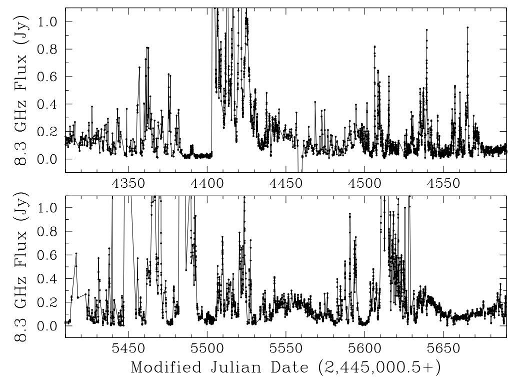

FIGURE 3. Short time scale flaring activities presented in the long-term 8.3 GHz radio light curve of Cyg X-3 observed by the Green Bank Interferometry

Since both sources are also persistent in X-rays, we can readily notice the flare event through, for example, the IAU Circulars or Astronomy Telegrams, and can perform the follow-ups in the radio. Therefore, GRS 1915+105 and Cyg X-3 are the best targets for the radio timing, accompanied with X-ray observation.

KOREAN VLBI NETWORK (KVN)

In VLBI arrays, the antenna spacings (or baselines) are hundreds to thousands of kilometers to achieve $\leq$ mas resolution. The signals from the antennas are independently recorded and correlated later (for details of VLBI, [10][11]).

The KVN system is a new VLBI project of the Korea Astronomy Observatory (KAO), started in 2000. The major scientific goal is mm-wave VLBI astronomy. A

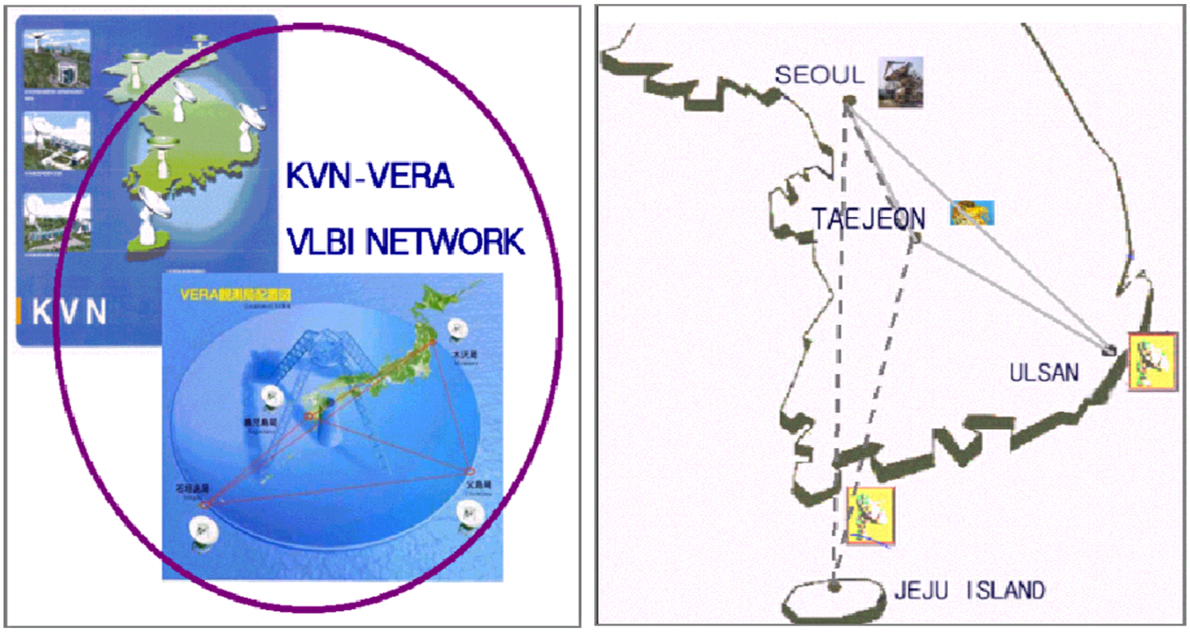

FIGURE 4. Left: Schematic view of the cooperative VLBI observations with three 21 m KVN (left) and four 20 m VERA (right hand side) antennas. Right: Two patrol-purpose arrays for detecting an initiation of the flare event to support VLBI observations of microquasar phenomena, with 6 m in Seoul, 14m in Taejeon, and a 21 m telescope from KVN VLBI system. The baselines for Seoul-Taejeon, Taejeon-Ulsan, Seoul-Ulsan and Taejeon-Jeju are 135, 194, 305 and 356 km, respectively. The longest baseline is 478 km for Seoul-Jeju.

few major areas have been proposed: masers in stars, star forming regions, gravitational lenses, extragalaxies, active galactic nuclei, quasars and microquasars.

Three 21 m antennas will be built at Seoul, Ulsan and Jeju island in Korea by 2006. All necessary facilities are planned to be completed by 2007. The KVN will be equipped with 2.5, 8.5, 23, 43, 86 and 129 GHz receivers, and, tentatively, an addition of a high frequency receiver up to 150 GHz. The expected resolution is from $\sim$70 mas at 2.5 GHz to $\sim$3 mas at 43 GHz. For higher frequencies, about 1 mas is currently sought for 86-129 GHz. The most probable lower limit for the detectable continuum flux would be about $\geq$ 100 mJy, together with $3-69$ mas resolution is expected at $2-43$ GHz [12]. In the future we wish to add three more antennas (for details of KVN, `http://www.trao.re.kr/~kvn`).

The most distinctive feature is the millimeter wave multi-channel receiver system for the phase calibration. By adopting this method, the KVN can simultaneously measure 23, 43, 86 and 129 GHz from the beginning, and, in addition, 150 GHz later on [13]. Similar to quasars, microquasars show a variety of spectral slopes: negative ($\alpha < 0$), flat ($\alpha = 0$) and inverted ($\alpha > 0$, where $S_\nu = \nu^\alpha$). The slopes have been determined based on radio observation in cm and only a few points in low frequency mm wavelengths [14][15][16]. To make this broad picture complete, the lack of high frequency mm observations from about 20 to a few hundred GHz, should be fulfilled. This is why the high frequency mm radio observations are necessary in microquasar and quasar research. In this sense, the KVN will be a unique, competitive probe to study the radio spectral distribution in microquasars and quasars.

KVN-VERA VLBI NETWORK

Maps of the multiple jet components in microquasars have been obtained in a few other black hole X-ray binaries (see Table 1 in [2] and references therein). To achieve detailed inner jet evolution in such multiple jet components, a few to a hundred of mas for the beam size is required. Since the KVN will temporarily have only three 21 m components, the Korea-Japan VLBI collaboration has been proposed. As a first step, VLBI test observations with Korean 14m and Japanese Nobeyama 45m telescopes have been carried out for last 3 years. We eventually will perform the Korea-Japan VLBI observations between KVN and recently launched Japanese VLBI network called VERA, VLBI Exploration of Radio Astrometry (for details, [17] and `http://veraserver.mtk.nao.ac.jp/`). VERA system is currently operated with four 20 m telescopes in Mizusawa, Iriki, Ogasawara and Ishigaki, equipped with 23 and 43 GHz receivers. In addition, Nobeyama 45m and Kashima 34m are also currently included as a part of the Japanese VLBI Network (J-Net) for VLBI at 23 GHz. The longest baseline in VERA is 2,300 km between Mizusawa and Ishigaki. In the long-run, with three 21 m telescopes for the KVN, we can carry out more extensive VLBI observations as a Korea-Japan collaboration.

KVN-TRAO-SRAO ARRAY: PATROL FOR DETECTING FLARING ACTIVITY IN MICROQUASARS

The exact time for a beginning of the flaring activity and associated jet event in microquasars is not predictable. There are several ways to initiate observing those microquasar phenomena in the radio: for example, checking up IAU Circulars and Astronomy Telegrams, or multiwavelength campaign. The former method is based on the fact that the radio event in general is followed by the X-ray flare.

Without any information of X-rays or campaign, the only way to know the right time to observe is a daily radio timing monitoring. We here propose such a patrol for radio flaring events to support successful, detailed KVN follow-up observations for microquasar phenomena.

In Korea we currently operate two mm single dishes: the Taeduk Radio Astronomy Observatory (TRAO) 14m and the Seoul National University Radio Astronomy Observatory (SRAO) 6 m telescopes in Taejeon and Seoul, respectively. Together with a 21 m KVN component, we can utilize 6 and 14 m to make an array. Simple estimation with typical parameters for 6 and 14 m, together with a 21 m KVN antenna, results in the followings: flux detection limit of $\sim 200-300$ mJy with $\leq$ tens of mas, assuming typical parameters of $\sim$128 MHz, $\sim$0.88, $\sim$0.5 and $\sim$300 K for bandwidth, efficiency factor, aperture efficiency and system temperature, based on the longest baseline (e.g., [10]).

Independent of any 21 m KVN component, we also can utilize one-baseline $6-14$ m interferometry for detecting a large flux change. It is reminiscent of similar VLBI experiments performed in Japan, with Kagoshima 6 m and Mizusawa 10 m, 1297 km apart, [18][19], resulting in $0.3-1.2$ mas resolution [20][21].

We therefore can recognize a sudden flux change, although the very beginning may not be detected, at least for known radio-bright microquasars such as GRS 1915+105 and Cyg X-3. As soon as we detect the on-going flares, the KVN can initiate its target-of-opportunity program for detailed follow-up observations, triggered by the flux monitoring with $6-14$ m interferometry, or with $6-14-21$ m array.

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